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ScienceDirect
Physics Procedia 72 (2015) 333 – 337
Physics Procedia

Conference of Physics of Nonequilibrium Atomic Systems and Composites, PNASC 2015, 18-20 February 2015 and the Conference of Heterostructures for microwave, power and optoelectronics: physics, technology and devices (Heterostructures), 19 February 2015

Experimental Comparison of Shock and Bubble Heave Energies from Underwater Explosion of Ideal HE and Explosive Composite Mixtures Highly Enriched with Aluminum

P.V. Komissarov[a,b]*, A.A. Borisov[a,b], G.N. Sokolov[b], V.V. Lavrov[c]

[a] *National Research Nuclear University MEPhI, Kashirskoye shosse 31, Moscow 115409, Russia*
[b] *N.Semenov Institute of Chemical Physics, Russian Academy of Sciences, Moscow 119991, Russia*
[c] *The Institute of Problems of Chemical Physics, Russian Academy of Sciences, Chernogolovka, Moscow regio 142432, Russia.*

Abstract

Experimental data on shock wave and bubble heave energies at underwater explosion of charges based on highly enriched with aluminium explosive mixtures are reported. Al/O ratios of the mixtures used are varied from 1.31 to 2.36. Al-rich charges up to 30 g were exploded in basin of 2 m in diameter and 5 m in depth. As a result, Al-rich mixtures used are demonstrates overall specific energies of underwater explosion up to twice higher than conventional high explosives.

Peer-review under responsibility of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)

Keywords: underwater explosion; aluminized explosives; nonideal explosion

Nomenclature

e_s	shock wave energy

* Corresponding author. *E-mail address:* kr_899@yahoo.com

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doi:10.1016/j.phpro.2015.09.105

e_b	bubble heave energy
m	charge weight
R	distance between the pressure gauge and charge
ρ_w	water density
c_w	acoustic velocity
P	shock wave pressure
P_m	maximal pressure at the shock wave front
P_h	hydrostatic pressure at the charge depth
τ_b	period of bubble pulsation

1. Introduction

Aluminized explosives are typically used in order to increase the shock wave and bubble heave energies of underwater explosions [1]. Aluminium contents in most of them are not exceed 20 wt. % [2]. However, some of recent works demonstrates a possibility to increase Al contents in explosive mixtures up to 50 wt. % and even more without losing detonability [3, 4]. Such mixtures capable to react in low velocity detonation regime in reasonably low diameters, using the inertial support of attached water mass [7]. Unfortunately previous works on underwater detonation of extremely enriched with aluminium explosive mixtures only demonstrates a possibility to obtain additional energy from reaction of excess aluminium with ambient water, without any measurements of shock and bubble energies. Direct comparison between the highly enriched with aluminium explosive mixtures with other well known underwater high explosives and mixtures (including aluminized compositions) have not yet carried out. As previous experiments [5-7] with small composite aluminum-rich charges (up to 10 g) exploded in small-scale water volumes (1x0.5x0.5 m) have shown, excess aluminium reacts quite efficiently and fast with surrounding water increasing significantly the overall specific explosion energy to values that are much greater than those inherent in energetic materials used at present in underwater explosion works. The aforesaid findings call for larger-scale tests with the use of appropriate instrumentation. In the present article, the results of experimental measurements of shock and bubble energies from underwater explosions of ideally and nonideally detonating charges in continuous water are reported. Charges weighing 30 g were exploded in a water-filled cylindrical metal reservoir with semi-elliptical bottom, sized 5 m in depth and 2 m in diameter. The charges were positioned at the axial line of the reservoir at a 1.5-m depth. Parameters of compression waves generated by explosions in the reservoir were measured with pressure gauges. The main goal of these investigations was estimation of the external effect of explosion of energetic materials highly enriched with aluminium in terms of shock wave and bubble heave specific energies, including the effect of excess aluminium reaction with surrounding water.

2. Experimental method used

Contemporary compositions used as underwater explosives are usually characterized by the oxygen weight content index. As seen from the comparison of the Al/O ratios in Table 1, in the compositions used in the present experiments, the aluminium fraction is much greater than that in conventional HE used for underwater works. The weight content of nitromethane (NM) in all compositions containing various amounts of aluminium we used was constant and equal to 17%. The Al/AP ratio alone was varied, from 1:1 to 2:1. Flaked aluminium PAP-2 with a representative particle size of 10x10x1 μ was used. Ammonium perchlorate particles were of a 40-μ mean size. First, we mixed solid components in a polyethylene bag. Then, a needed amount of nitromethane was introduced with a hypodermic syringe into the bag, and the mixture was stirred continuously. The resulting mixture looks as granules of size ranging between 0.5 and 1 mm. TNT was chosen as a basic HE, whose explosion parameters served as a reference in assessing performance of nonideally detonating mixtures.

The prepared compositions were poured in plastic enclosures made of a polyethylene tube 20 mm i.d. with 4-mm thick walls. The tube ends were sealed with a scotch tape. The mixtures were introduced by portions, each portion was compacted manually. The charge density was controlled. Thus, the mean density was constant throughout the charge length. The nonideal mixtures cannot be detonated directly with a conventional detonation cap. Therefore, a 4-g ammonite 6JV booster was poured on top of the mixture.

Table 1. Comparison of the Al/O ratio between the mixtures used and other conventional underwater explosives.

Energetic material	Composition (wt.%)	Al/O ratio
1:1 mixture	41.5%Al, 41.5% AP, 17%NM	1.31
1.5:1 mixture	50%Al, 33% AP, 17%NM	1.85
2:1 mixture	56%Al, 27% AP, 17%NM	2.36
Tritonal	70% TNT, 30% Al	1.02
RS [5]	Chinese mixture contains dinitroanisole, AP, RDX and Al particles	0.3732
PBXN-111 [5]	20 % RDX, 43%AP, 25 %Al, 8% HTPB-based polyurethane binder	0.4589
H-6 [8]	27.7% TNT, 43.1% RDX, 22.7% Al, 0.4% CaCl2 , 6.1% wax	0.369
HBX-3 [8]	31% RDX, 29% TNT, 25% Al, 5% wax	0.808

In experiments, a pressure-time histories were recorded with gauges located at the charge depth and at the half-way between the charge and reservoir wall (0,5 m from the charge). The total energy evolved used in a comparative analysis of the underwater explosion performance is normally assumed to be a sum of the shock wave energy and bubble heave energy. To assess the total energy we use calculation procedure reported in [8-10]: Normally, shock wave energy e_s is calculated by integrating the recorded pressure profile squared by a formula:

$$e_s = \frac{4\pi R^2}{m\rho_w c_w} \int_0^{6.7\tau} P^2 dt \,, \tag{1}$$

where R is the distance between the pressure gauge and charge, m is the charge weight, ρ_w is the water density at the gauge location site, c_w is the acoustic velocity at the depth where the charge is positioned with allowance for the ambient water temperature, τ is the representative time of the process, i.e. the time during which the pressure signal recorded drops from its maximum (at the front) to $P_m/e \approx 0.37P_m$ and P is pressure versus time.

According to Bjarnholt recommendations [10] the gauge must be positioned at a distance R from the charge obeying the following inequalities:

$$3.5 < \frac{R}{m^{1/3}} < 7, \ [\text{m/kg}^{1/3}] \tag{2}$$

However in our tests, the gauge was positioned closer to the charge than the minimum limit of its optimal location. This arrangement was dictated by the size of our reservoir and by the necessity of gauge placing some distance away from the wall in order to have some spare time for signal recording before the reflected wave arrives at the gauge. Therefore the energy e_s values, listed in the table must be considered as a qualitative criterion in a comparative analysis of the performance of nonideal charges instead of TNT. The bubble heave energy e_b is assessed by the formula from [10, 11]:

$$e_b = \frac{1}{8c_w^3 K_1^3}\left[\sqrt{1+4Ct_b\left[\frac{P_h}{P_{hn}}\right]^{5/6}}-1\right]^3 \tag{3}$$

Here K_1=1.135$\rho_w^{1/2}/P_h^{5/6}$, C is calculated as $C=b/a^2$, here a and b are constants. These constants are evaluated using the reservoir calibration procedure described in [10, 11].

3. Results and discussion

Results of experiments in term of energy evolved in the course of underwater explosion are presented in Table 2. Among the entire set of tests performed we selected only those reliability of which was unquestionable. Moreover we have repeated three times the tests with nonideal rich mixtures to be sure that their results are correct. Reference experiments were conducted with three ideally detonating HE (TNT, RDX and Tritonal). TNT experiments were performed with different masses of the charges including masses lower and higher than the nonideal charge mass used.

Table. 2. Summary of the experimental results.

Charge	m, g	e_s (e_s from[12]), MJ/kg	e_b, MJ/kg	$e_s + e_b$, MJ/kg
1:1	30	1.49	6.76	8,25
		1.36	7.34	8,7
		1.41	6.92	8,33
1.5:1	30	0.86	8.67	9,53
		0.94	9.0	9,94
		0.92	9.1	10,02
2:1	30	0.67	7.98	8,65
		0.64	8.03	8,67
		0.61	7.91	8,52
Tritonal	30	1.2(1.31)	4.77	4,97
RDX	30	1.24(1.39)	3.16	4,4
TNT	5	0.99 (1.01)	2.71	3,7
	10	0.94 (1.01)	2.69	3,63
	20	0.97 (1.01)	2.77	3,74
	40	0.98 (1.01)	2.89	3,87

The represented specific shock wave energy e_s was calculated by formula (1), its values are also presented in the Table together with the shock wave energy values based on experimental data from [12]. The assessed shock wave energy values for HE charges are qualitatively consistent with the available literature data however being slightly lower, which is accounted for by the cylindrical charge shape and, presumably, by errors of measurements inevitably arising when small weight charges are exploded (in [12] charges weighing few kilograms were used). Moreover, experiments with different masses of TNT charges demonstrate the same quantity of specific shock and bubble heave energies.

As seen in Table 2, the groups of experiments with nonideal charges also demonstrate similar results both in terms of shock wave energy and bubble heave energy. The increase in some energy ratios is ascribed to reaction of the excess aluminium with water. Particularly, 1.5:1 and 2:1 mixtures demonstrate higher bubble energy than the 1:1 mixture due to higher aluminium contents. In addition, insignificant differences in the bubble energy of 1.5:1 and 2:1 mixtures indicates that there is some optimal richness in aluminium, at least for the selected mass of the charge. It should be noted that the shock wave energy in the 1:1 mixture is higher than the shock energy observed in HE explosions, even in the case of RDX. As to the overall specific energies of underwater explosion, mixtures highly enriched with aluminium are about twice as powerful as the conventional HE.

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